Polyethylene Macroencapsulation

Mixed Waste Focus Area

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INNOVATIVE TECHNOLOGY
Summary Report

Polyethylene Macroencapsulation

OST Reference # 30

Mixed Waste Focus Area

Demonstrated at
Envirocare of Utah, Inc.,
Salt Lake City, Utah
Developed by
Brookhaven National Laboratory
Brookhaven, New York

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available online at http://em-50.em.doe.gov.

TABLE OF CONTENTS

APPENDICES

SECTION 1

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Technology Description

The lead waste inventory throughout the U.S. Department of Energy (DOE) complex has been estimated between 17 million and 24 million kilograms. Decontamination of at least a portion of the lead is viable but at a substantial cost. Because of various problems with decontamination and its limited applicability and the lack of a treatment and disposal method, the current practice is indefinite storage, which is costly and often unacceptable to regulators.

Macroencapsulation is an approved immobilization technology used to treat radioactively contaminated lead solids and mixed waste debris. (Mixed waste is waste materials containing both radioactive and hazardous components.) DOE has funded development of a polyethylene extrusion macroencapsulation process at Brookhaven National Laboratory (BNL) that produces a durable, leach-resistant waste form.

This innovative macroencapsulation technology uses commercially available single-screw extruders to melt, convey, and extrude molten polyethylene into a waste container in which mixed waste lead and debris are suspended or supported (Figure 1). After cooling to room temperature, the polyethylene forms a low-permeability barrier between the waste and the leaching media.

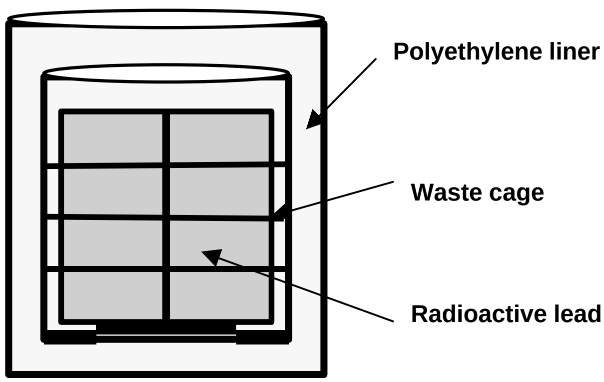

Figure 1. Cross-section of macroencapsulated final waste form.

Polyethylene macroencapsulation offers many technological and economic advantages:

- Polyethylene extruders are commercially available and have a long history of industrial use. Except for a specialized pour nozzle, the equipment and materials used in the process are available off the shelf.
- Polymer extrusion technology can be scaled or tailored to site-specific conditions and can be readily incorporated into existing treatment trains.
- Macroencapsulation offers low capital and operating costs and is readily commercialized.
- The process operates at low temperatures, needs no off-gas treatment, and generates only small quantities of recyclable secondary waste (i.e., molten polyethylene waste).
- The polyethylene encapsulate is one of the most commonly used polymers and is relatively inexpensive compared to other treatment processes. Polyethylene is extremely tough and flexible, has excellent chemical resistance, and is easy to process.

- Macroencapsulation produces a waste barrier that is durable, leach resistant, and compliant with Nuclear Regulatory Commission (NRC) guidelines and Resource Conservation and Recovery Act (RCRA) requirements for disposal of mixed waste lead and debris.

Demonstration Summary

Under a cooperative agreement (DE-FC07-95ID13372) between the DOE Idaho Operations Office (DOE-ID) and Envirocare of Utah, Inc., a polyethylene macroencapsulation process developed by DOE at BNL was transferred to Envirocare, whose facility is located approximately 80 miles west of Salt Lake City, UT. The polyethylene macroencapsulation extrusion process was demonstrated and implemented in fiscal year 1996 by Envirocare, which is fully licensed and permitted to treat and dispose low-level radioactive and mixed waste.

Under the terms of the cooperative agreement, each party contributed approximately equal resources of $1 million:

- Envirocare provided equipment and supplies, facility construction/modification, permitting, and personnel training.
- DOE paid for treatability studies for multiple waste streams and treatment and disposal of approximately 500,000 lb of mixed waste lead and debris.

Envirocare already had a RCRA permit to operate as a hazardous waste treatment/storage/disposal facility. The company was required to obtain a modification to its RCRA Part B permit from the state of Utah to operate the macroencapsulation equipment for processing mixed waste lead and debris. Under the cooperative agreement, waste streams were shipped to Envirocare from 23 DOE sites: Argonne National Laboratory–East, Battelle Columbus, Bettis Atomic Power Laboratory, BNL, Charleston Naval Shipyard, Energy Technology Engineering Center, Fernald, Formerly Utilized Sites Remedial Action Program (FUSRAP) Colonie Site, General Atomics, Idaho National Engineering and Environmental Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory (LANL), Laboratory for Energy-Related Health Research, Knolls Atomic Power Laboratory (KAPL), KAPL Kesselring Site, Mare Island Naval Shipyard, Nevada Test Site (NTS), Norfolk Naval Shipyard, Oak Ridge National Laboratory, Paducah Gaseous Diffusion Plant, Pearl Harbor Naval Shipyard, Pinellas, and Puget Sound Naval Shipyard.

- The Pinellas Site eliminated its entire remaining mixed waste inventory under the agreement. Under separate contracts, Fort St. Vrain and the Kansas City Plant also eliminated their entire remaining mixed waste inventories using macroencapsulation at Envirocare. Eighty Navy sites eliminated lead waste streams.

- The FUSRAP Colonie Site and NTS eliminated entire waste streams. DOE-ID and Envirocare extended the final completion milestone to include the remaining 500 lb of the NTS waste stream.

- DOE-ID, Envirocare, and LANL renegotiated the cooperative agreement to allow LANL to ship 60,000 lb of mixed waste lead, the site’s entire inventory, to Envirocare for treatment and disposal.

    - This change required an expansion of the cooperative agreement total processed waste quantity from 500,000 to 520,000 lb. LANL Waste Management Operations (EM-30) provided the additional budget (approximately $40,000) required to fund the expanded allocation.

    - LANL estimates a savings of more than $824,000 by working an agreement with Envirocare through the Mixed Waste Focus Area (MWFA) rather than negotiating a separate agreement.

Key Results

- High-melt-index polyethylene (>50 g/10 min) has better flow characteristics and produces higher quality final waste forms than the relatively low-melt-index polyethylene Envirocare used in the early stages of the demonstration and implementation.

- For large-scale pours, low-density polyethylene (LDPE) is more successful than high-density polyethylene because it has a lower shrinkage factor.

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Licensing Information

All equipment and materials are commercially available.

Other

All published Innovative Technology Summary Reports are available online at http://em-50.em.doe.gov. The Technology Management System, also available through the EM50 Web site, provides information about OST programs, technologies, and problems. The OST Reference # for polyethylene macroencapsulation is 30.

SECTION 2

Overall Process Definition

The polyethylene macroencapsulation extrusion process involves heating, mixing, and extruding the polyethylene in one basic operation. An extruder consists of four basic components: feed hopper, rotating augerlike screw, heat-controlled barrel in which the screw rotates, and an output die assembly to shape the final product (Figure 2).

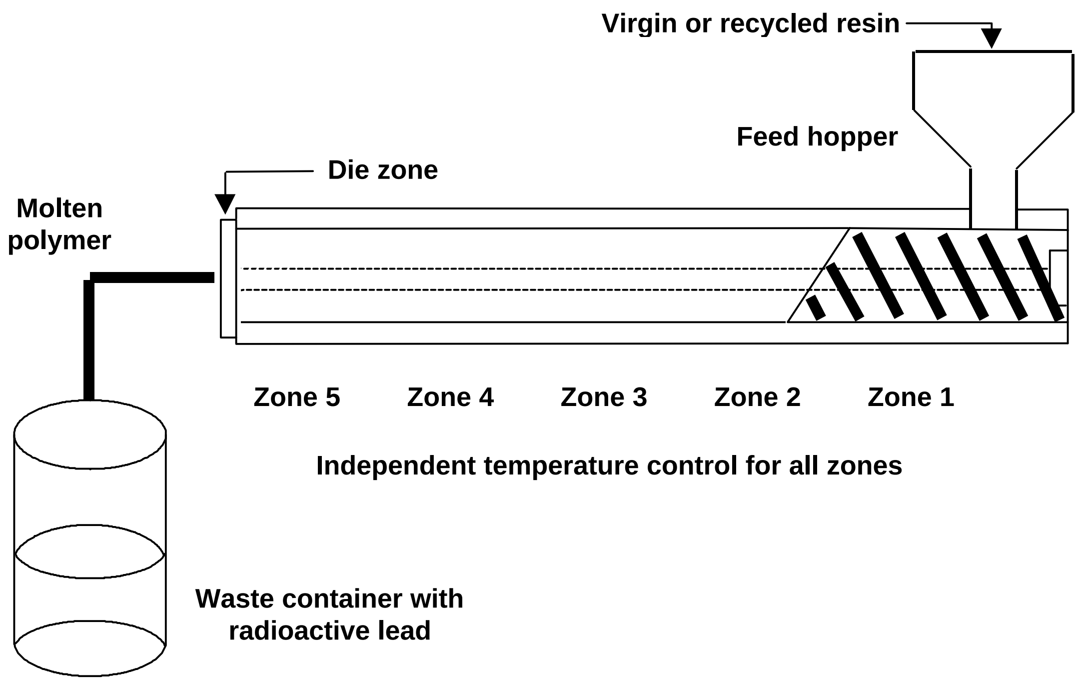

Figure 2. Macroencapsulation process schematic.

Envirocare used a Davis-Standard 11.4-cm (4.5-in) single-screw extruder with an output capacity of 900 kg/h (2000 lb/h).

- The extruder was equipped with five electric clamshell-type barrel heating zones and two die heating zones with thermocouple controllers to provide gradual heating of the polyethylene. A solid-state, dual-probe anticipatory temperature-control system held the barrel temperatures to ±1°F.
- The extruder cooling loop consisted of distilled water circulation; a flow-through, water-cooled heat exchanger; and individual zone flow indicators.
- The extruder was equipped with a two-stage screw driven by a 150-hp motor, feed transfer and metering sections in the first stage, and vent and metering sections in the second stage. (The vent is not needed for macroencapsulation applications.) A Maddock mixing section was at the end of the metering section.

The drag-induced flow associated with the rotating screw produces a pressure buildup that forces the fluid through the die.

- The rotating screw of a conventional plasticating extruder has three geometrically different sections:
  - The feed section has deep flights, and material is generally solid state.
  - The transition section connects the feed section and the metering section. The depth of the screw channel decreases linearly from the feed section to the metering section, thus causing a compression of material in the screw channel. Compression is essential to proper functioning of the extruder.
  - The metering section has shallow flights and is located closest to the die assembly.

- Once inside the extruder, the polyethylene is conveyed through the barrel by the motion of the rotating screw. As the polyethylene moves forward, it is masticated under pressure because of compressive effects of a gradual reduction in the channel area between the screw and barrel.

- The polyethylene is melted by the gradual transfer of thermal energy from shear energy produced by the screw and from electric heaters mounted on the barrel. The heat buildup from barrel friction cannot be consistently predicted and must be compensated for by regulating the resistance band heaters using external blowers.

- A Maddock mixing section at the end of the metering section increases dispersive mixing, producing a more homogeneous thermal profile in the extrudate and more consistent flow characteristics:

  - Longitudinal splines in the mixing section force molten polymer over barrier flights.
  - The Maddock mixer is a pressure-consuming section reducing the output of the extruder.
  - The longitudinal geometry with constant channel depth results in a stagnant region; thus, this design is not suitable with materials of limited thermal stability.

  Because polyethylene is a thixotropic material, the extra shear energy (frictional heat) imparted by the Maddock mixer also reduces the viscosity of the extrudate.

- The melted polyethylene is conveyed from the extruder at 300–350°F (150–160°C) and is usually poured directly into the waste container, where it flows around and into the waste matrix voids, completely encapsulating the waste. The LDPE melt has sufficient heat capacity to provide a fusion bond at the cold LDPE interface, resulting in a continuous monolithic pour.

- Because of the properties of polyethylene, approximately 3% shrinkage will occur upon cooling. This shrinkage must be accounted for in developing waste container configurations.

For the initial demonstration, Envirocare used virgin high-density polyethylene with a melt index of 2 g/10 min. This particular polyethylene was chosen because Envirocare planned to augment its polymer feed with recycled plastics. This plan proved impractical for two reasons:

- The extrudate was overly viscous and would not flow around the waste without manual assistance (hand-packing) by the operators.

- Recycled plastics have inconsistent properties batch to batch, making them inefficient for production-scale operations.

Envirocare modified its process to use LDPE with a melt index of 24 g/10 min. Although LDPE with higher melt indexes flows better, it is more prone to cracking. Currently, Envirocare blends LDPE with melt indexes of 2 g/10 min and 60 g/10 min to create a composite melt index of 9 g/10 min. This formulation flows freely enough to fill voids in the waste matrix without hand-packing, while minimizing cracks.

SECTION 3

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Demonstration Plan

Envirocare conducted technology demonstrations during fiscal year 1996 to support its permitting process. Prior to this test phase, state of Utah regulators witnessed polymer encapsulation process demonstrations at Rocky Flats Environmental Technology Site (RFETS). During the demonstration at Envirocare, Utah regulators worked with researchers at BNL to better understand the macroencapsulation process. These interactions greatly influenced Envirocare's RCRA permit requirements as defined by the Utah regulators.

Concurrently, the MWFA issued a letter to solicit interest throughout the DOE complex for participation in the cooperative agreement. Twenty-three sites responded, and more than one thousand tons of waste was identified for inclusion in the demonstration. The MWFA developed a seminar package to train participants to complete the waste profiles required by Envirocare. Waste shipment began in early summer 1996.

Treatment Performance

The encapsulating polymer used during the initial demonstration phase of the cooperative agreement was not well suited for production-scale operations. The relatively low melt index (2 g/10 min) of virgin LDPE resulted in overly viscous extrudate that had to be hand-packed in the waste receptacle. Envirocare tried materials with melt indexes of 24 g/10 min and then 60 g/10 min, finding that the higher melt index polyethylene was prone to cracking.

Envirocare experimented with composite LDPE mixtures until determining that LDPE with a melt index of 9 g/10 min (made by blending materials with melt indexes of 2 and 60 g/10 min) provides an optimum feed stock for production-scale operations. During the demonstration phase and throughout the cooperative agreement, Envirocare continued to expand its process capabilities. The process has now been proven effective for package sizes ranging from 5-gal buckets to full 55-gal drums in 110-gal overpacks.

Based on results of the demonstration phase at Envirocare and interactions with BNL and RFETS, Utah state regulators imposed specific waste acceptance criteria for the macroencapsulation process, examples of which are discussed below.

- Surface-coating material must be of one of the following two types:
  - Polymeric organics (e.g., resins and plastics) are acceptable, but nonpolymerics such as waxes are not allowed. Plastic wrap is also unacceptable.
  - Jackets of inert materials are allowed but must be composed of metal or inorganic materials; metal jackets must be in direct surface contact with macroencapsulated material through lamination, welding, molten pouring, or similar technique. Other inorganic materials may be used as jackets, but they must not be carbon-based compounds or substances.
- Cracks or gaps in the macroencapsulation monolith can result in substantial surface exposure to leaching media. This possibility led to the following waste acceptance criteria:
  - Waste shall not protrude through the surface or the waste form.
  - The waste form shall be created to prevent interior voids or air pockets containing waste.

- The preceding requirement has been superseded by the following: Nonwaste protrusions from hangers or spacers may be present. Such protrusions shall be cut off at the surface of the waste form. Gaps between the encapsulation material and such protrusions are not acceptable.
- Buoyant waste forms can “float” when the waste is placed in planar arrays and back-filled with flowable grout. To prevent this, waste forms submitted for disposal must have a minimum density of 70 lb/ft^3 (about 1.1 g/ml).

- Utah originally required minimum coverage around the waste form of 2 in. of polyethylene to meet the regulatory specification to reduce potential for exposure to leaching media. However, thick layers of LDPE have a tendency to crack, with higher melt indexes being the worst. Consequently, Utah modified the Envirocare permit and waste acceptance criteria as follows: “…a minimum exterior surface-coating thickness of 1 in. for waste forms up to 30-gallons (4 ft^3) and 2 in. for larger volumes unless a demonstration is made to and approved by the Executive Secretary for an alternative minimum thickness based on waste type.”

SECTION 4

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Competing Technologies

The Debris Rule (57 FR 37194, August 18, 1992) identified extraction or destruction technologies as alternatives to macroencapsulation of debris wastes. The materials sent to Envirocare were not decontaminable. Mixed waste processed at Envirocare under the cooperative agreement had already undergone unsuccessful decontamination attempts because of volumetric contamination.

Polymer encapsulation was devised as an alternative to grout/cement encapsulation. The advantages of polymer encapsulation are lower leachability and permeability and greater impact resistance, durability, and resistance to environmental degradation after disposal.

At least two other polymer macroencapsulation technologies are available:

- Several companies offer container-type technologies for macroencapsulation. Waste is placed in premanufactured polyethylene containers and the containers are sealed using a variety of techniques. Fillers can be added to minimize void space in the container. One such technology developed by Arrow-Pak has been implemented at Hanford. It involves supercompaction of “soft waste debris” (e.g., Tyveks, Kimwipes) in 55-gal drums into “pucks” that are then overpacked in a polymer sleeve and sealed. However, these systems are acceptable only for macroencapsulation of debris. A technology ruling equivalent to 40 CFR 268.42(b) would have to be obtained to use this process for radioactively contaminated elemental lead.

- Thermoset polymer encapsulation technologies are also available. These technologies are attractive for their flexibility and high mobility, but base resin costs are significantly higher than those of polyethylene.

Technology Applicability

Macroencapsulation is specifically limited to treatment of radioactively contaminated elemental lead and mixed waste debris. Macroencapsulation has been successfully demonstrated on several mixed waste streams, including radioactive lead, leaded gloves, debris contaminated with beryllium fines, and filters.

Polymer encapsulation technologies are appropriate for the wastes sent to Envirocare because they are contact-handled wastes with half-lives <30 years. Low levels of ionizing radiation (<100 megarad) will not adversely impact the structural integrity of the final waste form. Testing conducted at BNL indicated that polymers could withstand an accumulated radiation dose of 100 megarad without significant hydrolysis.

Macroencapsulation is not appropriate for any RCRA Land Disposal Restricted (LDR) material other than radioactive lead solids (D008) or hazardous debris as defined by RCRA.

Technology Maturity

- Screw-type extruders were first employed in the United States by the rubber industry and were adapted for the extrusion of various thermoplastics in 1938. The use of extruders to process various thermoplastic materials is commonplace in industry today.

- Polymer macroencapsulation has been extensively tested at Rocky Flats (Getty and Riendeau 1995).

- Polymer extrusion technology can be scaled or tailored to site-specific conditions and can be readily incorporated into existing treatment trains or manufacturing processes.

Patents/Commercialization/Sponsor

Envirocare of Utah, Salt Lake City, UT has acquired this technology from DOE through Cooperative Agreement DOE DE-FC07-95ID13372. There are no known patents issued.

Twenty-three federal sites participated in the cooperative agreement macroencapsulation program at Envirocare. Cooperative Agreement DOE DE-FC07-95ID13372 is the primary end-user sponsorship document. Envirocare issued certificates of disposal to all sites that participated in the cooperative agreement.

Envirocare has also treated radioactively contaminated lead solids and mixed waste debris using the macroencapsulation technology for nonfederal entities.

SECTION 5

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Methodology

Implementation of macroencapsulation at Envirocare was effected through a cooperative agreement between Envirocare and DOE-ID.

- Under the agreement, Envirocare paid for equipment and supplies, facility construction/modification, permitting, and personnel training. Envirocare acquired an amendment to its operating license from the state of Utah to macroencapsulate mixed waste. Under the cooperative agreement, Envirocare also provided facilities for treatment and disposal of these wastes.

- DOE paid for the treatment and disposal of approximately 500,000 lb of mixed waste lead and debris using polyethylene macroencapsulation technology.

Cost Analysis and Conclusions

Capital Costs

- The appropriate polymer extruders for this application cost between $50,000 and $160,000. Actual costs incurred by Envirocare are considered proprietary information and not disclosed.

- Ancillary equipment, such as feed hoppers and transfer systems, total approximately $10,000.

Operating Costs

- Approximately 500,000 lb of radioactively contaminated lead bricks was encapsulated in LDPE and disposed of in Envirocare’s RCRA Subtitle C disposal facility for a cost to DOE of approximately $1,000,000, or $1.92/lb. This amount includes substantial treatability study activities and is based on the process as it existed at the time. This cost also includes resources for Envirocare to experiment with scale-up and process improvement efforts.

- Current contracting cost for polymer macroencapsulation at Envirocare is dependent on the amount and type of waste to be processed. However, a reasonable range is between $\$90/ft^3$ and $\$100/ft^3$. (Envirocare does not base treatment contract costs on a per-pound basis.)

- Commercial surface decontamination of lead costs approximately $2.00/lb. Recent experience has shown that up to 50 percent of contaminated lead cannot be sufficiently decontaminated for clean recycling purposes. Consequently, this material must be treated in accordance with LDRs and disposed of. The following brief analysis contrasts the costs of disposal of 500,000 lb of contaminated lead through polymer macroencapsulation with those for decontamination of the same amount with a 50 percent release rate:

Disposal	500,000 lb @ $1.70/lb	$850,000
Purchase of new lead	250,000 lb @ $0.35/lb	87,500
Total		$937,500
Decontamination	500,000 lb @ $2.00/lb	$1,000,000
Disposal of waste lead	250,000 lb @ $1.70/lb	425,000
Total		$1,425,000

- Polyethylene macroencapsulation operating costs at a DOE site average approximately $800/55-gal drum. These costs are based on the following assumptions:

  — There is a 1-in annular space between the drum and the waste.
  — Virgin polyethylene is used as the encapsulating material. Significant cost savings may be realized using recycled plastic.
  — Downdraft tables or glove bags are used for radiation containment.
  — The process uses two operators.

- Because macroencapsulation is an approved treatment technology, waste form qualification testing is not required. Off-gas monitoring is also not required. These factors lead to significant cost savings compared to destruction and separation technologies.

- Virgin LDPE costs approximately $0.61/lb or less depending on purchase volume. Recycled material costs about one-third as much, but supplies of appropriate recycled LDPE tend to be unreliable.

- LANL estimates a savings of more than $824,000 for treatment of its 60,000 lb of radioactive lead by working an agreement with Envirocare through the MWFA rather than negotiating a separate agreement.

SECTION 6

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Regulatory Considerations

The waste streams treated in this demonstration were subject to the Resource Conservation and Recovery Act (RCRA) but not the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

- By RCRA definition, macroencapsulation is specifically limited to treatment of radioactively contaminated elemental lead solids and mixed waste debris.

- Macroencapsulation, which is the RCRA technology-based treatment standard for radioactively contaminated elemental lead, is defined in 40 CFR 268.4 as "Application of surface-coating materials such as polymeric organics (e.g., resins and plastics), or use of a jacket of inert inorganic materials to substantially reduce surface exposure to potential leaching media." Macroencapsulation specifically does not include any material that would be classified as a tank or container according to 40 CFR 260.10.

- The Debris Rule defines macroencapsulation as encapsulation with "surface-coating materials such as polymeric organics (e.g., resins and plastics) or use of a jacket of inert inorganic materials to substantially reduce surface exposure to potential leaching media." This definition does not include the container restriction that is identified for macroencapsulation of lead.

- Currently, macroencapsulated debris contaminated with a listed waste must be managed as a RCRA hazardous waste. Proposed regulatory modifications (i.e., DOE's response and recommendations to the U.S. Environmental Protection Agency's proposed Hazardous Waste Identification Rule) would exclude immobilized mixed debris from RCRA Subtitle C restrictions after treatment. This exclusion would be similar to the one provided for hazardous debris treated by extraction or destruction technologies.

- Permit requirements for implementation of this technology at other facilities are expected to include

  — RCRA permitting depending on site-specific requirements,
  — National Environmental Policy Act review (categorical exclusion), and
  — radioactive materials license.

  Air permits are unlikely to be required.

- Because macroencapsulation is a technology-based treatment standard, the process used must be approved by local regulatory agencies as meeting the definition of MACRO, as provided in 40 CFR 268.2 prior to disposal in a RCRA Subtitle C landfill.

- Radiological exposures to personnel must be kept "as low as reasonably achievable" pursuant to DOE regulations.

Worker Safety Issues

- Hughes Associates evaluated the relative fire hazards associated with a production-scale polyethylene extrusion process. The results of the study indicate that fire hazards associated with the process are common to industrial extruder processes and not unique to the intended application. Fire hazards associated with the extruder include the potential for overheat conditions, electrical power faults, and ignition of combustible lubricants. The primary fire hazard associated with the polyethylene extrusion process is the storage of raw polyethylene, but the hazard is minor because of the low flammability of polyethylene.

- Molten polyethylene can cause severe burns, so precautions for worker safety are necessary.

- A properly operated polymer macroencapsulation process requires minimum operator input other than drum placement at the output of the extruder.

- Level B or C personnel protection is required depending on waste characteristics and process ventilation.

Community Safety, Potential Environmental Impacts and Exposures

The risk to community is very low. Macroencapsulation waste barriers meet LDR requirements, and the physical process used to encapsulate waste has very low accident and release potential.

Benefits

- Polymer extruders are easy to install and operate.

- The process operates at low temperature, needs no off-gas treatment, and does not generate secondary wastes.

- The process produces compliant, leach-resistant, and durable final waste forms.

- The process has low profile and requires little space.

Potential Socioeconomic Impacts and Community Perceptions

- Polymer macroencapsulation has minimal economic or labor force impact.

- The polymer extrusion macroencapsulation process is not generally considered to be a viable alternative to incineration. As pointed out earlier, this process is not cost-effective for “soft debris,” which is primarily combustible waste and can be incinerated.

- No adverse public or tribal input regarding macroencapsulation technology was received. Stakeholders have expressed preference for this technology over cement/grout encapsulation technology because of long-range stability.

SECTION 7

[redacted]

Technology Selection Considerations

- Polyethylene macroencapsulation is a good treatment option for lead and debris wastes contaminated with low levels of radioactivity.

- The technology is competitive with separation and destruction technologies for debris wastes contaminated with low levels of volatile organic compounds.

- Polyethylene macroencapsulation has been demonstrated at Envirocare and various DOE sites to be effective in the treatment of radioactively contaminated lead and debris wastes.

- Several studies have been conducted to evaluate the long-term mechanical stability of the final waste form. In particular, the waste form's response to biodegradation, photodegradation, radiolysis, chemical attack, and fire were examined:

    — Polymers are highly resistant to microbial attack. Ecological concerns over the ability of plastics to resist microbial degradation have precipitated numerous studies on the biodegradability of plastics and potential techniques for enhancing it. All of these studies concluded that, under normal conditions, biodegradation rates for polyethylene are negligible.

    — Photodegradation of polyethylene exposed to ultraviolet radiation can cause deterioration of structural integrity; however, this failure mechanism is unlikely since radioactive waste forms are not exposed to the sun.

    — Low levels (<100 megarad) of ionizing radiation will not adversely impact the structural integrity of the final waste form. Four chemical reactions are generally responsible for the effects of radiation on polyethylene: cross-linking, chain scission, increased unsaturation, and oxidation. Of these, cross-linking is the predominant effect. Increased unsaturation has little effect on the mechanical properties, but it occurs with nearly the same yield as cross-linking. Each of these two reactions results in the production of hydrogen on a 1:1 basis. Chain scission is a minor reaction, occurring at a rate of about 5 percent of cross-linking and increased unsaturation. Oxidation is generally neglected, but it could play a significant role. The occurrence of each of these reactions is linearly dependent on the absorbed dose of radiation.

    — Experiments conducted to evaluate the thermal stability of the waste form conclusively demonstrated that no exothermal reaction hazards exist. In the event of a hot fire, however, the waste form is likely to burn. The flash-ignition temperature of polyethylene is 340°C, and the auto-ignition temperature is 430°C.

    — Polyethylene's resistance to chemical attack is one of the main reasons for its widespread use in many diverse applications. At ambient temperatures, polyethylene is insoluble in virtually all organic solvents and is resistant to many acids and caustic solutions.

Implementation Considerations

- LDPE with a melt index of approximately 9 g/10 min has adequate flow characteristics with minimal surface cracking, as compared to material with extremely low (2 g/10 min) or extremely high (60 g/10 min) melt indexes. This material provides a cost-effective production-scale process with higher quality final waste forms.

- Because it has a lower shrinkage factor, LDPE is more successful than high-density polyethylene for large-scale pours.

- The annular space between the waste and the container is a critical parameter in ensuring complete coverage and minimizing cracking.

- To minimize fire hazards associated with the process, a Hughes Associates study recommended the use of noncombustible lubricants, thermal limit switches to shut down the extruder in the event that a heating unit overheats, and routine maintenance and cleaning. Hughes Associates also recommended limitations on the quantity and arrangement of stored polyethylene to reduce the fire hazard.

Technology Limitations and Needs for Future Development

- The rationale for minimum layer thickness, leaching performance, durability, and effect of void spaces should be addressed, particularly since some of these issues affected the acceptance criteria for Envirocare. Development of technically defensible positions on these issues will assist in future regulatory review and permitting processes and lead to a more cost-effective final waste form.

- Research should be conducted to determine whether compaction technologies should be incorporated with macroencapsulation to improve waste loading.

- The polymer encapsulation process with LDPE is relatively intolerant of the presence of free liquids and organics. Encapsulation of mixed waste forms containing free liquids or organics will require additional investigation and site-specific regulatory interaction and approval.

APPENDIX A

[redacted]

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